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Structural Features of a Solar TPV Systems

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Abstract. Developed solar TPV system consists of sunlight tracker, sunlight concentrator, absorber of concentrated sunlight, selective emitter of radiation, internal reflectors of radiation from the emitter, and PV cells cooled by water or forced air. The concentration ratio exceeding 8000 suns is ensured by the developed 300W dish mirror with secondary compound parabolic concentrator. The emitter is made of tungsten evacuated in a vacuum bulb. To decrease the losses of the photons emitted back to outside of TPV system, the area of the emitter surface exceeds up to 10 times the absorber aperture area. The developed PV cells based on Ge and GaSb have a back-surface mirror, which reflects the sub-bandgap photons to the emitter increasing its temperature and overall system efficiency.

INTRODUCTION

Solar thermophotovoltaic (STPV) conversion [1-11] is based on a principle of the intermediate conversion of concentrated solar energy into radiation from heated emitters with subsequent photovoltaic conversion of this radiation by low-bandgap photoconverters. Significant reserves for an increase in solar TPV efficiency lie in possibilities for secondary action of photoconverters on a radiation source, that is, the non-used photons can be reflected back to the radiator assisting in keeping it hot. Such a possibility is completely absent in solar power PV systems. Therefore, STPV device is a complex and more closed system, which should be more effective, if the principle of radiation recirculation is used. Additional way for STPV converter efficiency increase is the development of selective emitters matched to the PV cells. This selective emitter should radiate at $h\nu > Eg$ and weakly at longer wavelengths. A similar role is played by an optical filter; this component is included in the TPV systems to return sub-bandgap-energy photons back to the emitter to re-heat it. This optical element can be made as dielectric stacks (in a separate component or deposited on the cell or emitter) or as a metallic reflector on the back surface of the cells. In other words, combination of filters, metal reflection of the cell back for low energy photons and selective emitters we have considerable room for shaping the spectrum of the energy used by a cell.

The potential efficiency of STPV converter expected in practice exceeds 30%. These estimations are in correspondence with experiments of the monochromatic radiation conversion of photons with the energy just a little bit larger than the cell bandgap. Efficiency of 56% was measured in a GaAs cell under monochromatic radiation at the wavelength of 850 nm, and ETA = 49% was detected in a GaSb cell under 1680 nm radiation [12].

SUN-TRACKERS

Concentration ratios as high as 5000x and more, which are necessary for effective application of a solar TPV converter, require a high accuracy of tracking to the sun. Tracking accuracy much better than the sun angle size has to be achieved around both axes. In order to develop complete practical concentrator systems, different prototypes of the stand-alone photovoltaic/battery-powered tracking systems were designed and fabricated by us. Experimental tracking systems for the total input aperture of 1.5 m^2 and 5 m^2 were built up. Each tracker consists of two main moving parts: a base platform moving around the vertical axis, and a suspended platform with TPV modules moving around the horizontal axis. Figure 1 represents the main features of such a design.

In these installations the base platform is equipped with three wheels one of which is connected with an azimuth drive. In this case only a flat ground territory is necessary for the tracker operation. The suspended platform is a three-dimensional frame. The concentrator modules are installed within this frame so that a balance is achieved around the horizontal axis. The frame can rotate from vertical position (sunrise/sunset) up to horizontal position (if the sun is in zenith).

a) *b)*

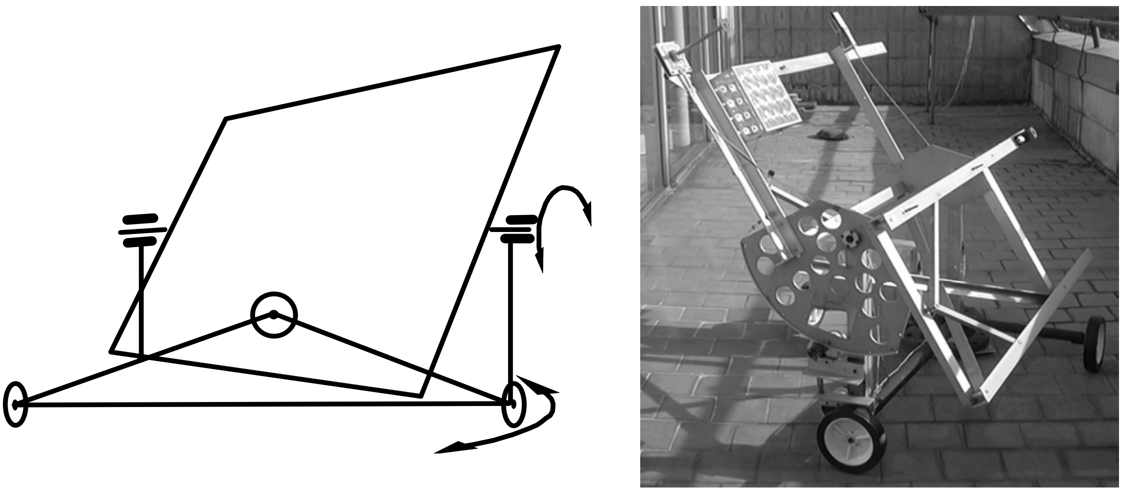

FIGURE 1. Mechanical diagram (a) and photograph (b) of the tracker for solar TPV systems.

Tracking mechanisms are fully automatic managed by analog sun sensors. Each PV installation is equipped with a main (accurate) sensor and an additional one. The main sensor can align the tracker with the sun to within 0.05 degree of arc accuracy with acceptance angles of ±70° in both horizontal and vertical directions. The additional sensor makes the “East/West” turning angle wider (up to 270°, if necessary).

The main sun sensor is mounted on the suspended platform and has an ordinary configuration. It consists of four PV cells (two for azimuth, and two for elevation) placed on a flat plate. The sensor is protected from environments by a flat silicate glass window sealed in contour with a structural hermetic. At a distance of 10-15 cm in front of the plate with cells, another square plate is situated. It shadows in part all the cells being directed to the sun. Two differential signals are generated in the main sensor corresponding to misalignments in azimuth and elevation channels.

The additional sun sensor consists of two PV cells identical to those used in the main sensor. The cells are situated on the opposite sides of a special plate. This plate has to be orientated by its edges always from South to North (with low enough accuracy) independently of the tracker orientation. Besides, the additional sensor is equipped with a shadowing element moving in accordance with movement of the suspended platform along azimuth direction. The latter may be a part of the main sensor. Differential output of the additional sensor is connected in parallel with that of the azimuth channel in the main sensor.

The tracker with input aperture area of 1.5 m^2 (see photograph in Figure 1,*b*) is situated on the roof of the Ioffe Institute. Suspended platform has a two-step three-dimensional structure where the concentrator TPV modules with the total input aperture of 1.5 m^2 can be arranged. Both platforms are moved by identical drives. Each drive consists of a miniature DC motor and a gearbox. The azimuth gearbox is mechanically connected with one of the wheels moving along the ground. The elevation gearbox is equipped with a small roll connected with a quadrant attached to the suspended frame.

Beside sensors and electronic circuits described above, the tracker is equipped with a portable 12 V Ni-Cd battery and an overcharge controller. The battery is charged from a concentrator PV module (it is shown in Fig. 1,*b*) based on 16 series connected single-junction GaAs solar cells.

TWO-STAGE SUNLIGHT CONCENTRATORS

To achieve high efficiency of the concentrator-emitter system at high emitter temperatures, a radiation concentration ratio must be sufficiently high which can be achieved by the use of a two-stage concentrator (Fig. 2), consisting of the Fresnel lens or compound spherical/parabolic mirror and a secondary lens or compound parabolic concentrator (CPC).

The developed CPC has the reflecting inner surfaces of special form with the inner surface generated by a rotating parabola section. The advantage of a CPC for STPV system is that it does not produce the sun image, mixing rays from different parts of the primary mirror, but strongly increasing power density. It ensures more uniform illumination of absorber in TPV system in comparison with lens secondaries.

Efficiency of the system with a two-stage concentrator exceeds appreciably that of the one-stage concentrator system, and the optimum angle φ (Fig. 2,b) is considerably lower: the optimum φ values are around 50-60° for the one-stage concentrators whereas these values for the two-stage concentrators are only 20-30° [14]. It is more advantageous to use the CPC with long-focus mirrors, which are relatively easy to fabricate. Figure 3 shows the fabricated Fresnel lenses and Fig. 4 – the fabricated compound spherical mirror. The concentration ratio up to 8000-12000 suns is ensured by the developed two-stage concentrator (Fig. 2,*b* and 4) based on primary dish concentrator and secondary CPC.

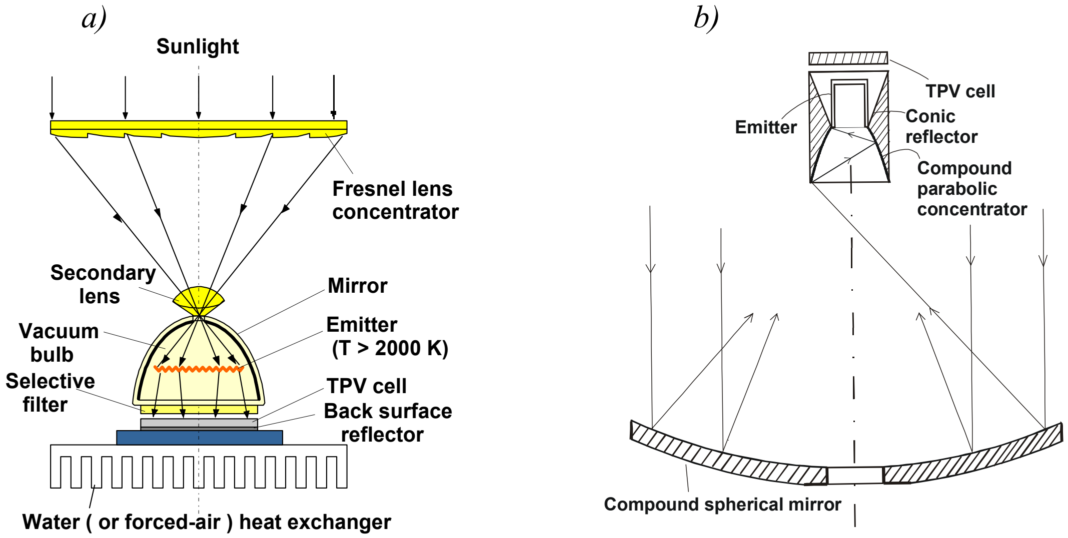

FIGURE 2. Schematic of the STPV systems based on two-stage concentrators with primary Fresnel lens (*a*) or dish mirror (*b*) and secondary lens (*a*) or CPC (*b*).

Achievable concentration ratio and efficiency of the STPV system based on Fresnel lenses are lower than in the spherical/parabolic mirror system. Nevertheless, utilizing cheaper Fresnel lenses allows the cost reduction of solar electricity. Therefore, STPV systems with Fresnel lenses are under development as well.

FIGURE 3. Fabricated Fresnel lenses with dimensions of 27cm x 27cm and focal distance of 30 cm designated for fabrication of 4 solar TPV modules.

FIGURE 4. Compound spherical mirror fabricated for TPV system: - maximum diameter of 86 cm; - focal distance of 75 cm.

SOLAR TPV MODULES

The goal of this part of the work is the development of solar TPV modules, which should ensure the increase of the system efficiency owing to the decrease of losses in the TPV converter. The solar thermophotovoltaic system under development consists of a sunlight tracker, a two-stage sunlight concentrator, an absorber of concentrated sunlight, a selective emitter of radiation and water cooled PV cells with a back surface reflector.

Two different module types (Fig. 5,6) were developed with "cylindrical" shape of the emitter, filter and photoreceiver and with plane (disk, square) module elements. In the both cases the absorber and the emitter are situated in vacuum that ensures the possibility to use a high-temperature tungsten emitter and provide thermal insulation. Calculations show that achievable emitter temperature would exceed 2000 K in the developed system at decreased losses of concentrated sunlight energy and radiation from the emitter.

To decrease the losses of the photons emitted back to outside from TPV system, the area of the emitter surface should exceed in 5-10 times the absorber aperture area. Three different designs of absorber/emitter were investigated: - an absorber and an emitter made of graphite; - an absorber made of graphite with an emitter made of a tungsten wire; - both an absorber and an emitter made of tungsten.

All internal surfaces of the receiver body free from PV cells have a mirror gold cover to reduce the losses of photons, which are not absorbed by PV cells. The developed PV cells based on Ge and GaSb have a back-surface reflector, which reflects sub-bandgap photons to the emitter increasing its temperature.

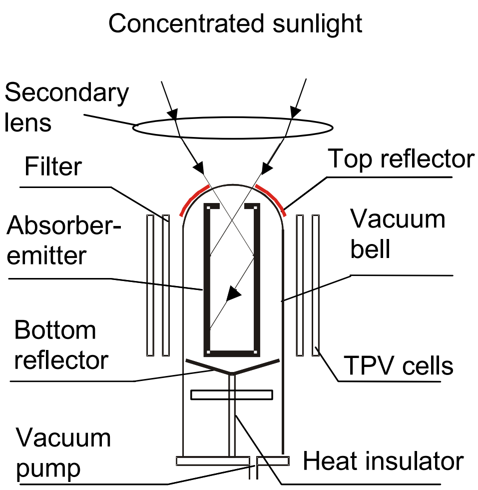

FIGURE 5. Schematic of the developed solar TPV systems of "A"-cylindrical type.

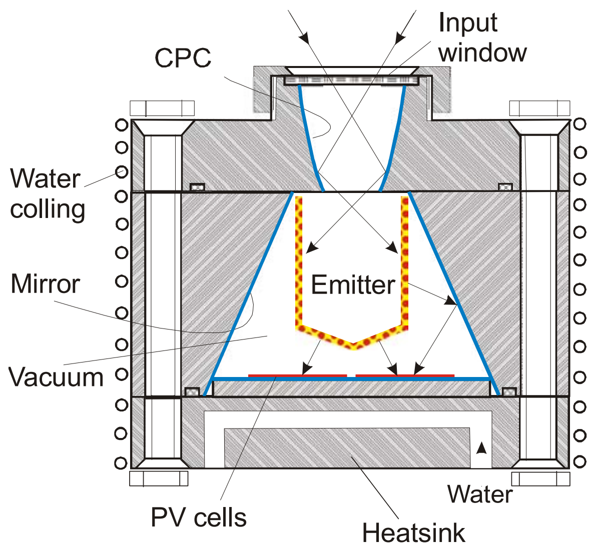

FIGURE 6. Schematic drawing of "B"-flat type solar TPV module - metallic vacuum chamber.

To obtain a high back-surface reflection, the sub-bandgap photons have to pass through the cell with minimal absorption to the back contact, by which they are reflected back to the emitter. The cell substrate should be relatively lightly doped (~ 10^{17} cm^{-3}) to reduce free-carrier absorption (without noticeable increase of the back contact resistance). To provide highly reflective interface between the semiconductor (Ge, GaSb) and the back surface contact, the alloyed regions (dots) occupying a small fraction (2-3%) of the cell surface were formed. The remaining area was covered with MgF_2 (SiO_2, Si_3N_4) and highly reflective metal (Au, Ag with intermediate adhesive layer). Photon reflectance R_{bs} = 85% for sub-bandgap photons was obtained in Ge-based TPV cells with a back-surface mirror and R_{bs} = 65% was measured in GaSb cells.

The "flat" and "cylindrical" photoreceivers were fabricated on the basis of the developed Ge and GaSb cells [11]. Figure 7 shows the 16 GaSb cells fabricated for cylindrical photoreceivers. Illumination I-V curve in Fig. 8 shows the good performance of these cells at photocurrent densities up to 5 A/cm^2. High-power photovoltaic plane array based on 16 (1x1 cm^2) GaSb TPV cells was fabricated for the TPV device of type "B". Output electric power of 17 W was detected in this photoreceiver at photocurrent of 60 A under a flash lamp.

Figure 9 shows that maximum photocurrent densities of the developed GaSb TPV cells could exceed 40 A/cm^2 at the emitter temperature T_E > 2200 K for the case when photoreceiver collects all photons radiated from the emitter and the photoreceiver of equal areas. Efficiencies as high as 27-28% are achievable in GaSb cells with return efficiencies of 90% at emitter temperatures exceeding 1900K. The curves in Fig.9 were obtained on the basis of the measured cell parameters: spectrum of external quantum yield, open circuit voltages and fill factors at photocurrent densities up to 130 A/cm^2. In the "cylindrical" module type (Fig. 5) the photoreceiver area is approximately in 10 times smaller than that of the emitter that leads to the proportional decrease of the cell photocurrent densities at the same emitter temperatures.

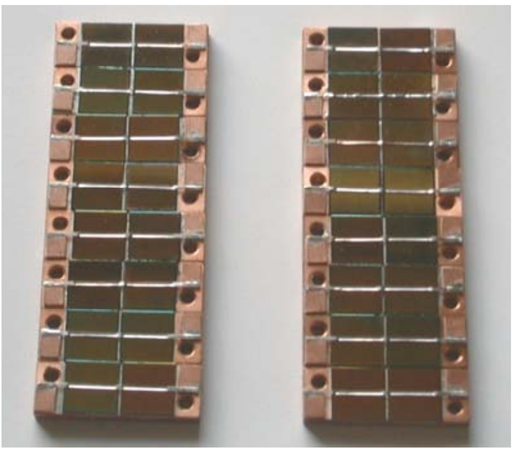

FIGURE 7. 16 TPV 1x2 cm^2 GaSb cells (made from 1x1 cm^2 peaces) mounted on the copper heat-sinks.

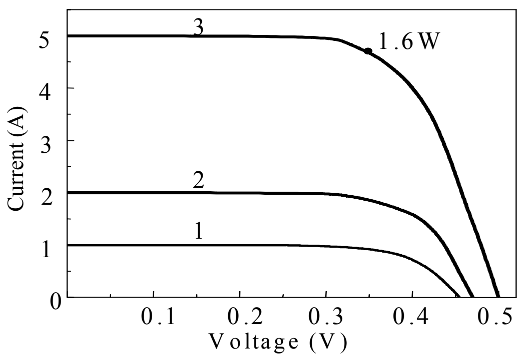

FIGURE 8. Illumination current-voltage characteristics of a 1 cm^2 GaSb TPV cell 1,2, - CW operation, 3 – flash lamp illuminated.

The ability of GaSb cells to operate with extremely high efficiency under the monochromatic illumination was demonstrated earlier [13]. Efficiency as high as 44% was obtained in these cells at j_{sc} = 10 A/cm^2 and up to 48-49% at j_{sc} = 40-100 A/cm^2 under the radiation with wavelength of 1680 nm.

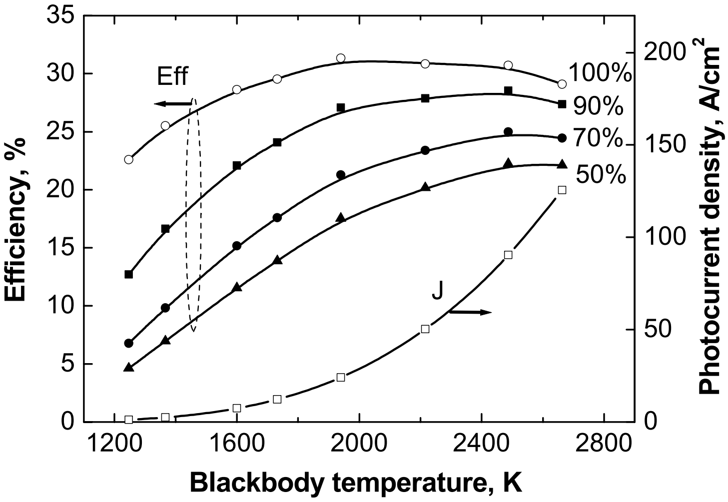

FIGURE 9. Photocurrent density and conversion efficiencies of the developed GaSb TPV-cell (area of 0.04cm^2) as a function of the black-body emitter temperature at the cell return efficiencies of 50%,70%,90% and 100%.

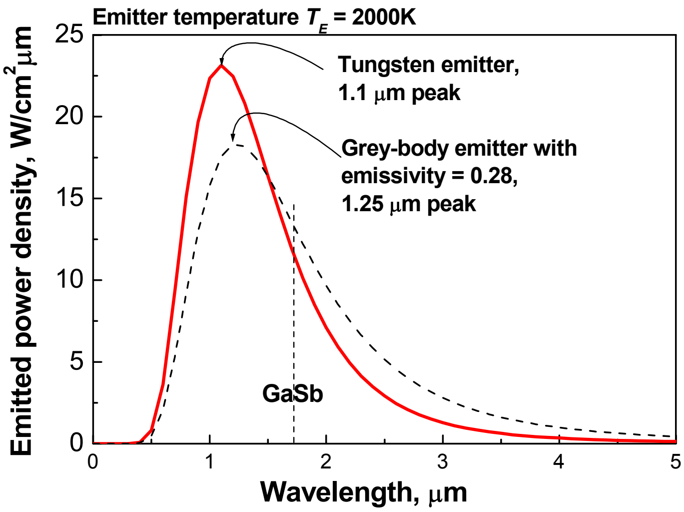

FIGURE 10. Calculated spectral shift of emission with the use of a tungsten emitter in comparison with a grey-body emitter at the temperature T_E = 2000 K

In utilization of a selective emitter (for example, made of tungsten), the efficiency would increase owing to better matching in the radiation and PV cell photosensitivity spectra. Figure 10 shows the spectra of tungsten and grey-body emitters at 2000 K. It is clear that the radiation maximum of the tungsten emitter is shifted toward the short-wavelength part of the spectrum. Amount of the long-wavelength radiation with energies lower than *Eg* (GaSb), therewith, decreases essentially.

Figure 11 presents the results of efficiency calculations for the system being developed at the moment [11]: - a 0.45 m^2 primary mirror; a two stage (dish mirror + CPC) concentrator with concentration ratio of 8000x; - the emitter is made from tungsten in a vacuum bulb. Improved GaSb cell parameters expected in advanced devices [12] have been assumed in these calculations, that gives a better efficiencies values in Fig. 11 for grey-body emitter in comparison with the efficiencies shown in Fig.9 for the developed GaSb cells. The comparison of a nonselective emitter (grey-body) and a selective emitter (tungsten) is made for advanced GaSb cells (Fig.11). The efficiency of the system based on the cells with return efficiency of 90% increases from 30% for the grey-body emitter to 36% for the tungsten emitter.

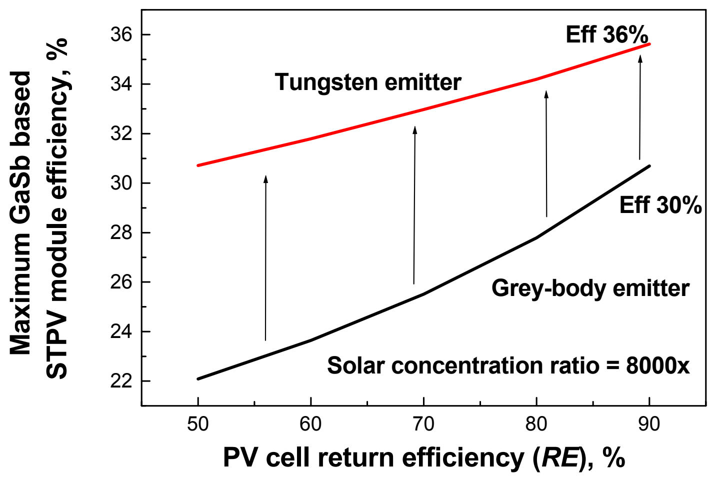

FIGURE 11. Calculated dependence of maximum GaSb based STPV module efficiency vs PV cell return efficiency for tungsten and gray-body emitters. Optimal emitter temperatures are in the range of 2000-2200K at concentration ratio of about $8 \cdot 10^3$ suns.

CONCLUSION

All necessary components for solar TPV devices (suntrackers, concentrators, emitters and photoreceivers) have been fabricated and are available for outdoor testing. Theoretical estimations show promises for the efficiency increase in the developed TPV devices, components of which are characterized by a high sunlight concentration ratio (> 8000 suns), high expected emitter temperature (> 2000 K) and a good TPV cells performance. Developed TPV cells based on GaSb can have the conversion efficiency of 28% under the black-body radiation (T > 2000 K) if cell return efficiency of 90% is achieved. Realization of advanced technologies for the cell and emitter fabrication should allow to increase the STPV system efficiency up to more than 35%.

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